MULTIPORT SOLR CALIBRATIONS: PERFORMANCE AND AN ANALYSIS OF SOME STANDARDS DEPENDENCIES

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Abstract

Short-Open-Load-Reciprocal (SOLR) has been used as a calibration technique when the realization of a good thru line is difficult. This may happen in on-wafer environments (e.g., when probes are orthogonal or when two-signal probes are used), in coaxial measurements (when different connector types are involved), or in fixtured measurements. The increasing number of multiport S-parameter measurements has further pushed demand for such an algorithm as probe and connector configurations proliferate. Several issues related to a practical implementation of multiport SOLR measurements are covered in this paper including thoughts on optimal combinations of thrus and reciprocal networks when choice is available, some limits on the behavior of reciprocal networks and how they affect standards choices, and a heuristic analysis of the use of redundant thrus/reciprocals in the multiport environment. Load match benefits the most from true thrus, when available, but transmission tracking seems less sensitive for a wide variety of networks. Thus, a careful selection of standards employed can, in some sense, optimize the multiport calibration in this environment.

Introduction

The SOLR calibration algorithm is extremely useful in situations where it is difficult to realize a true thru line [1]-[3] as is particularly true in wafer level calibrations (e.g., [2]). It is important to note the dependence of standard calibration algorithms on the perfect thru assumption. In SOLT, the transmission tracking and load match terms will be critically affected by insertion loss/length deviations in the 'thru' standard (or an inaccurate characterization of those quantities), and to a lesser degree, mismatch. The LRL/LRM/TRL/LRRM family of calibrations are not very dependent on the insertion behavior of the line for that is determined during the calibration, but they are critically dependent on mismatch. Deviations from match ideality (which can be thought of as a wandering reference impedance in some sense) ripple through to all error coefficients. Thus in situations of a highly defective thru, an alternative is needed.

The SOLR concept can be thought of as a hybrid of SOLT and TRL-class algorithms in that the reflectometer terms (directivity, reflection tracking and source match) are found through a short-open-load sequence but the remaining terms are found with the measurement of a relatively unknown network. Transmission tracking and load match are found through the measurement of an unknown network and related switch correction parameters. The algorithm is detailed elsewhere (e.g., [1], [4]) but the important concept is that this network need only be reciprocal

and that an estimate of its electrical length be available for a root choice. The S-parameters of the network are determined as part of the calibration process.

It is of some interest to determine practical limits on the parameters of this reciprocal network. Obviously if loss or reflection coefficients get too high, then the physical limits of the VNA will be reached (e.g., noise floor) causing the algorithm to fail but it may be useful to know if issues are likely to arise with more commonly used networks. It would also be useful to know what impact this network has on basic calibration quality (transmission tracking and load match) for those cases when a quasi-true thru may be available but only slightly inconvenient or somewhat poorly characterized.

In moving to a multiport formulation, one can follow a fairly standard multiport structure [5] in which a base two port calibration is expanded upon by 'thru' connections to additional ports. Assuming the same network is used for all additional port interconnects as was used between the first two ports, this procedure is possible since the network's parameters were determined during the first step. This technique does, however, limit flexibility in setup and is vulnerable to cascading errors since previous calculation results are heavily reused. While intermediate approaches are possible, we simply assume that the OSL reflectometer measurements are performed at each port and concentrate on possible thru/network assignments. Three port SOLR has been discussed previously [6]; the present technique is a simple generalization of the base work [1] to N ports using a fully coupled VNA.

It has been shown that for an N-port system, a total of N-1 'thrus' are needed assuming all ports are thru-connected at some point [5]. All load match terms are found during those steps and the remaining transmission tracking terms can be found via redundancy with reflection tracking terms (making certain assumptions about the behavior of reference coupling and other issues). In the case of SOLT, the differences between using all N(N-1)/2 thrus and the above approach are generally small although there are cases of cascading errors since calculation results are reused. It will be examined here if the use of SOLR results in a difference.

Procedure

The following experiments will use coaxial and fixtured environments for simplicity (frequency range limited by the fixturing) but the conclusions should be global. The calibrations will be 4 port (on a standard 4 port VNA or a 2 port VNA with a switching test set) with short, open, and load measurements performed at each port. A variety of combinations of thrus and different reciprocal networks will then be examined. In each case, the test DUT will be a balanced delay line, see Fig. 1, of low loss (< 0.5 dB over the frequency range of interest) that allows the best examination of transmission tracking and load match behavior.

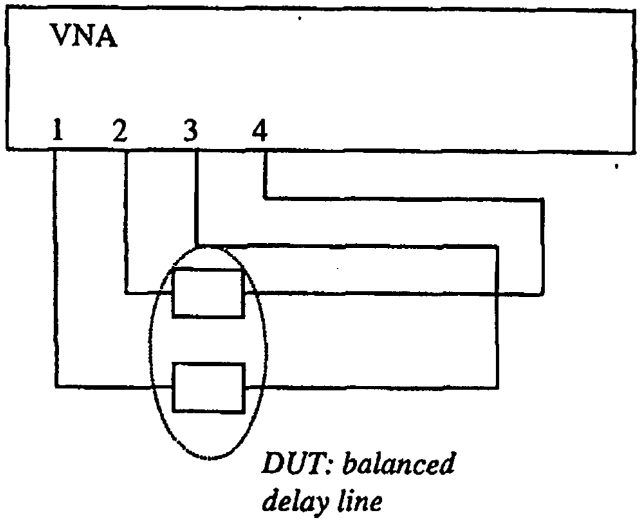

Figure 1. *A drawing of the test configuration is shown here. A four port calibration is performed in all cases using variations of thrus and networks. The delay line DUT was chosen for its ability to examine load match and tracking behavior.*

<u>Examples</u>
The first situation of interest arises when a true thru may be available but slightly inconvenient. In this case, it would be useful to know the penalty in invoking SOLR. The differential match of the delay line is perhaps one of the easiest quantities to look at in this regard. Comparing SOLT (true thrus) and SOLR using a 3 dB pad or a 10 dB pad as the network, the quasi-load match results are shown in Fig. 2.

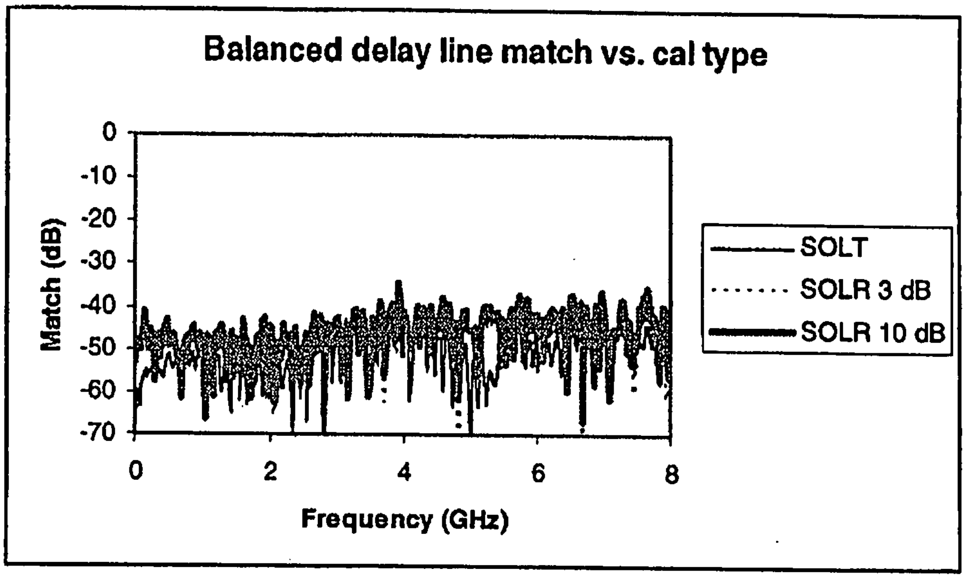

Figure 2. Differential match of a balanced delay line is shown here as a function of calibration type: SOLT with a real thru, SOLR with a 3 dB pad as the network, and SOLR with a 10 dB pad as the network.

As can be seen, there is some degradation in observable match as might be expected from the reduction in information but this degradation is small (equivalent to a residual at the ~ -45 dB level). The average match for SOLT was -50.4 dB while that for the 3 dB SOLR was -47.0 dB and for 10 dB SOLR, it was -46.8 dB. An interesting point is that the loss of the network seems to have little effect for losses between 3 and 10 dB. From other experiments, little additional degradation has been seen for 20 dB network loss. As would be expected, the SOLT advantage disappears with thru line quality degradation as has been pointed out previously (e.g., [2]).

To look at the effect on transmission tracking, one of the more sensitive parameters is deviation from linear phase (equivalently, group delay could be used). This experiment will examine a comparison between SOLT and SOLR and any differences occurring when the relevant transmission tracking terms are found directly or derived from earlier measurements (using redundancy). A comparison of the (port) 2-4 phase deviation is shown for SOLR (3 dB network, 2-4 network not used), SOLR (3 dB network, 2-4 network used) and SOLT (2-4 network used) is shown in Fig. 3.

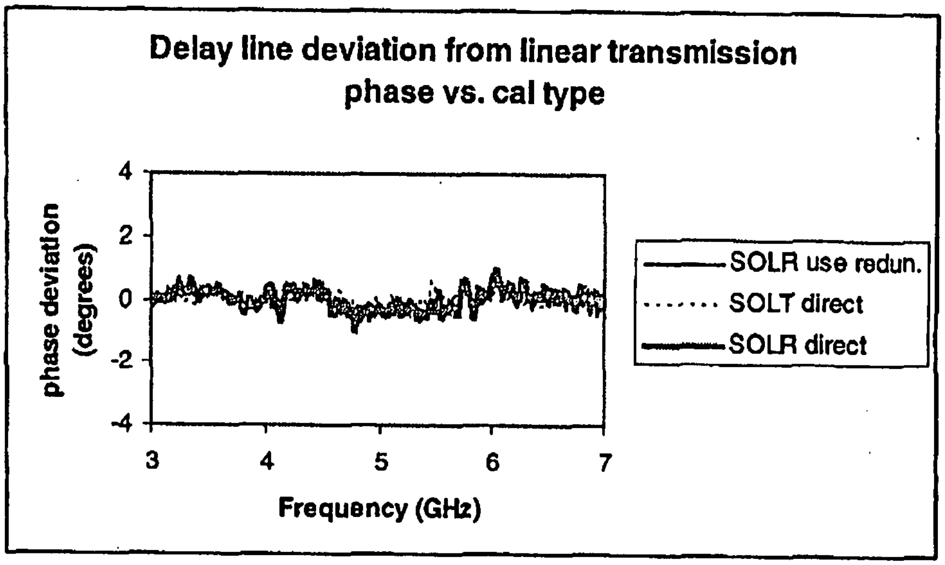

Figure 3. Deviation from linear phase for the 2-4 arm of the delay line is shown here versus calibration type. In one case, the 2-4 transmission tracking term was found using only redundancy and the directly found tracking terms for 1-2, 1-4 in SOLR. In the other two cases, the 2-4 tracking term was found directly using either SOLT or SOLR.

Most of the residual phase wander is due to the delay line network itself and some residual cable flex effects. Several interesting observations can be made here:

1) No substantial difference between using the direct network connect (2-4) or using redundancy to compute that tracking term 2-4.
2) No substantial difference between SOLT and SOLR in terms of tracking (at this level).

This experiment was rerun but in the case where the network was a highly reflective (and radiating) fixtured transmission line segment. This was chosen to emulate very poor networks as might occur in a GSSG (ground-signal-signal-ground) probing environment at higher frequencies. The network had a match of 15 dB or better below 6 GHz but starts approaching 10 dB at 7 GHz. The deviation from linear phase results are shown in Fig. 4.

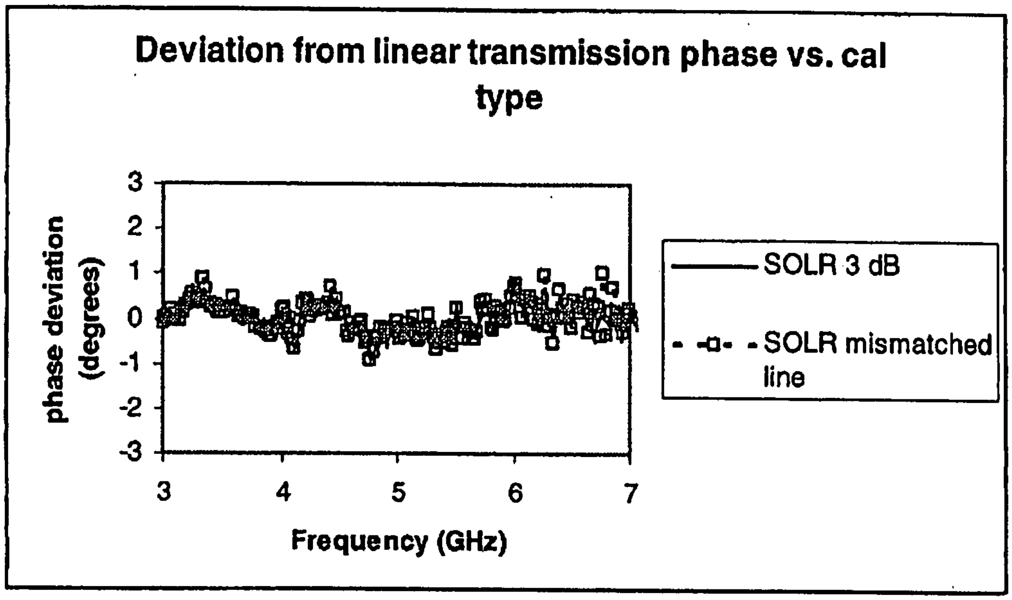

Figure 4. Deviation from linear phase for the 2-4 arm of the delay line is shown here versus network type for two SOLR calibrations. One was a 3 dB pad while the other was a mismatched in-fixture transmission line. The behaviors are very similar until the line's match gets worse than about -12 dB (between 6 and 7 GHz, measured separately).

In this case, some differences between SOLR with the well-matched network and with this other network can be observed in the frequency range where the second network's match is particularly poor. This would be consistent with a further loss of information during the calibration (because of network loss and fewer assumptions), a less accurate switch correction (multiple reflections), and associated errors.

Also of interest is the situation in which available thru line (for SOLT) quality degrades. While this certainly happens in curved line scenarios in wafer probing, it can also be an issue in coax/fixtured environments at higher frequencies. In this case, consider a 'thru' that has a minor increase in insertion loss between 8 and 12 GHz (due to a weak connector interface resonance it is presumed). A delay line was again used at the DUT, this one known to have about 0.2 dB insertion loss at 10 GHz with a monotonic frequency response. The measurement was performed using SOLT (with this questionable thru) and two versions of SOLR: one with a 10 dB pad as the reciprocal and one with a mismatched 25 dB pad (about -20 dB match above 10 GHz). The results are shown in Fig. 5.

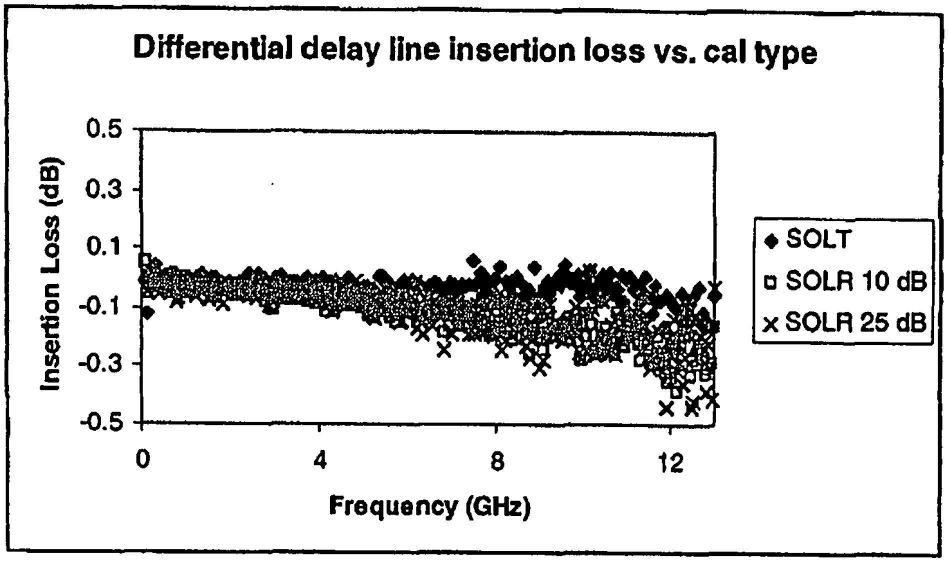

Figure 5. Delay line insertion loss as a function of calibration type is shown here. The thru used for SOLT had an increase in insertion loss above 8 GHz that mapped to the measurement result.

As might be expected, SOLT returned somewhat more deviant results since the thru line loss anomaly was not corrected. The SOLR with a 10 dB pad as the network returned a more reasonable result. The SOLR with the 25 dB pad produced a mean in-line with expectations but the data was noisier; this being a result of getting somewhat closer to the noise floor during calibration in this wider IF bandwidth (compared to the previous experiments) measurement. The poorer match of this 25 dB loss network may have also contributed to the degradation.

A final example can illustrate the cascading error concept. In this case, only 1-2, 1-3 and 1-4 thrus are used. A defect is present in the 1-2 thru measurement (large anomalies in S12 and S21 due to a bend). In the SOLT case, this error cascaded to other transmission tracking terms resulting in a glitch in the S24 phase deviation as shown in Fig. 6. The network connection from SOLR had a similar defect but since assumptions were not made, there was no error to cascade through.

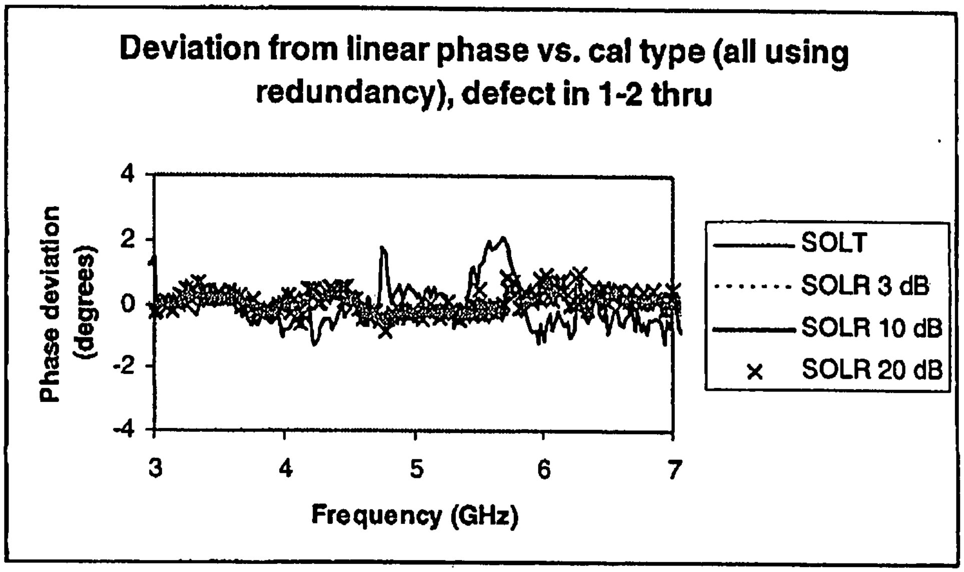

Figure 6. The delay line deviation from linear phase vs. calibration type in which all calibrations used redundancy to compute the 2-4 tracking term. The 1-2 'thru' had a defect which mapped to many tracking terms for SOLT but did not affect the SOLR calibrations with various networks (all had a similar defect in the 1-2 network connection).

Conclusions

Some multiport SOLR measurements have been presented to begin to illustrate the effects of network and redundant connection choice. While quite preliminary, some simple observations can be made:

- Load match is perhaps best handled by a direct thru if possible. Ideally, every port would be connected during a thru step. In a North-South-East-West on-wafer probe configuration, this is possible.
- The reciprocal network does not penalize transmission tracking over a wide range of losses but can have some issues if the match of the network is quite poor. The choice of using an extra network or using redundancy to compute remaining transmission tracking terms may be dependent on the parameters of the network. If the available thru line is of poor quality (and/or poorly characterized), the reciprocal network has obvious advantages.
- As in most redundancy cases, the choice of using extra steps may be dependent on confidence in the main steps (or the use of a statistical method). SOLR is somewhat more immune from defects and cascading errors in that fewer assumptions are used. This gives computation via the use of redundancy somewhat more power.

References

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